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Article (Published Version)

Hindawi
Advances in High Energy Physics
Volume 2018, Article ID 7168480, 8 pages
https://doi.org/10.1155/2018/7168480

Research Article

Composite Higgs Models after Run 2

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Received 30 October 2017; Revised 22 January 2018; Accepted 1 February 2018; Published 18 March 2018

Academic Editor: Alexey A. Petrov

We assess the status of models in which Higgs is a composite pseudo-Nambu Goldstone boson, in the light of the latest 13 TeV Run 2 Higgs data. Drawing from the extensive Composite Higgs literature, we collect together predictions for the modified couplings of Higgs, in particular examining the different predictions for κ_V and κ_F. Despite the variety and increasing complexity of models on the market, we point out that many independent models make identical predictions for these couplings. We then look into further corrections induced by tree-level effects such as mass-mixing and singlet VEVs. We then investigate the compatibility of different models with the data, combining Run 1 and recent Run 2 LHC data. We obtain a robust limit on the scale f of 600 GeV, with stronger limits for different choices of fermion embeddings. We also discuss how a deficit in a Higgs channel could pinpoint the type of Composite Higgs model responsible for it.

1. Introduction

Composite Higgs models [1–3] offer an elegant solution to the hierarchy problem of Higgs physics. They postulate the existence of a new strongly interacting sector which confines not far above the electroweak scale. In recent years there has been significant interest in a specific class of these models: models in which the Higgs emerges as a pseudo-Nambu Goldstone boson of the strong sector. This sector is taken to be endowed with a global symmetry which is spontaneously broken in the confining phase, protecting the Higgs mass from corrections above the compositeness scale. Although the idea is reasonably straightforward, there are, as with most theories Beyond the Standard Model, many possibilities for its realisation.

Although this plethora of models offers a variety of unique and interesting predictions, those that are most immediately testable are the modifications of the Higgs couplings to the rest of the Standard Model fields. Of particular interest are the values of the coupling modifiers κ_V and κ_F, as defined in [4].

In this paper we summarise the predictions for these couplings in Composite Higgs (CH) models. We make the case that, despite the diversity of models in the literature, these predictions have very generic structures, and we attempt to provide some intuition for this fact.

We then investigate some simple cases in which tree-level effects can modify these generic structures. These can occur, for instance, in models with extra singlets that get vacuum expectation values (VEVs) or models with an extra $SU(2)_L$ doublet that mixes with the Higgs. We point out that to leading order the modifications to κ_V and κ_F are precisely as one would expect in corresponding models where all the scalars are elementary, plus the usual CH corrections.

Taking the generic structures we have identified, we then perform a χ^2 fit to the data, allowing for the possibility that different fermions couple in different ways. We place bounds on the compositeness scale f and identify the classes of models that are most constrained.

2. The Nonlinear Composite Higgs

In Composite Higgs models, the Higgs is realised as a pseudo-Nambu Goldstone boson (pNGB) of a broken global symmetry. This symmetry is a symmetry of a *new* strongly interacting sector, out of which Higgs emerges as a composite.

Let the global symmetry be denoted by $\mathscr{G}$ and the subgroup to which it spontaneously breaks be denoted by $\mathscr{H}$.

Then Higgs and the other pNGBs (denoted collectively by ϕ^a, one for each broken generator X^a) are parametrised via

$$U = \exp\left(\frac{i\phi^a X^a}{f}\right), \quad (1)$$

where f is an energy scale associated with the spontaneous symmetry breaking. U transforms nonlinearly under the global symmetry $\mathscr{G}$:

$$U \longrightarrow gUh^{-1}, \quad (2)$$

where $g \in \mathscr{G}$ and $h \in \mathscr{H}$. By nonlinear we mean that the transformation h is field-dependent: $h = h(g, \phi^a)$.

In cases where the coset $\mathscr{G}/\mathscr{H}$ is symmetric (If T^a and X^a are the unbroken and broken generators respectively, then the Lie algebra of a symmetric coset obeys the schematic relations $[T,T] \sim T$, $[X,X] \sim T$, $[T,X] \sim X$.) we are allowed to construct an object (which we will label as Σ) whose transformation under $\mathscr{G}$ is *linear*. In all the models considered here [3, 5–22] and in the vast majority of models in the literature, $\mathscr{G}/\mathscr{H}$ will be symmetric. This reduces the task of writing down a low-energy effective theory for the pNGBs to a relatively trivial search for invariant combinations of Σ and the other relevant fields.

We will assume that the Higgs boson is a doublet under $SU(2)_L$, which, along with $U(1)_Y$, must be embedded as an unbroken subgroup of $\mathscr{G}$. Although data strongly supports the doublet scenario (e.g., see LHC constraints on the ratio of couplings to W and Z bosons [4]), nonlinear models have been studied in which the four scalar fields are actually a singlet and a triplet under $SU(2)_L$ [23–26] (note, though, that one could assume a custodially symmetric strong sector as in [27, 28]).

2.1. Gauge Couplings. The couplings of Higgs to the gauge bosons come from the kinetic term for Σ, which in the CCWZ prescription [29] is

$$\mathscr{L}_{\text{kinetic}} = \frac{f^2}{4}\operatorname{tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right], \quad (3)$$

where $D_\mu = \partial_\mu - igA_\mu$, with $A_\mu = A_\mu^a T^a$ for each gauged generator T^a. We assume that Higgs is embedded in a bidoublet $(\mathbf{2},\mathbf{2})$ of a custodial $SO(4) \simeq SU(2)_L \times SU(2)_R \in \mathscr{H}$; this is necessary in order to protect the ρ parameter from unwanted corrections [30]. Note that this imposes the nontrivial requirement that $\mathscr{H}$ must contain an unbroken factor of $SO(4)$.

Since we are interested in the couplings of the physical Higgs boson to SM fields, we will expand Σ along the direction in which Higgs will get a VEV and set all other pNGB fields to zero. The term in (3) will generically (in unusual cases the coupling may be proportional instead to $\sin^2(H/(2f))$, but all this amounts to is a redefinition of ξ and an effective rescaling of f) lead to a Higgs-gauge coupling of the form,

$$g^2 f^2 A_\mu A^\mu \sin^2\left(\frac{H}{f}\right), \quad (4)$$

which is valid as a series expansion around H/f.

Expanding around Higgs VEV $H \to \langle H\rangle + h$ (where h is the physical excitation of the Higgs field) we find the gauge boson masses and couplings:

$$\begin{aligned}\mathscr{L}_{\text{gauge}} \supset{} & \frac{1}{8}g^2 f^2 \sin^2\left(\frac{\langle H\rangle}{f}\right) W_\mu^a W^{a\mu} \\ & + \frac{1}{8}g^2 f \sin\left(\frac{2\langle H\rangle}{f}\right) W_\mu^a W^{a\mu} h \\ & + \frac{1}{8}g^2 \cos\left(\frac{2\langle H\rangle}{f}\right) W_\mu^a W^{a\mu} h^2.\end{aligned} \quad (5)$$

Identifying (here v is defined as $4M_W^2/g^2$, as in the Standard Model) $v = f\sin(\langle H\rangle/f)$ and defining $\xi = v^2/f^2$, we find

$$\begin{aligned}\mathscr{L}_{\text{gauge}} \supset{} & \frac{1}{8}g^2 v^2 W_\mu^a W^{a\mu} + \frac{1}{4}g^2 v\sqrt{1-\xi}\, W_\mu^a W^{a\mu} h \\ & + \frac{1}{8}g^2 (1-2\xi) W_\mu^a W^{a\mu} h^2.\end{aligned} \quad (6)$$

Thus,

$$\begin{aligned} g_{WWh} &= \sqrt{1-\xi}\, g_{WWh}^{\text{SM}}, \\ g_{WWhh} &= (1-2\xi)\, g_{WWhh}^{\text{SM}}.\end{aligned} \quad (7)$$

Since κ_V is defined as $g_{WWh}/g_{WWh}^{\text{SM}}$, we find

$$\kappa_V = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi. \quad (8)$$

Since the structure of (3) is generic, so too is this result, at leading order, across all Composite Higgs models.

2.2. Fermion Couplings. In Composite Higgs models the SM fermions usually couple to the strong sector via the *partial compositeness* mechanism [8, 31, 32]. As far as this mechanism pertains to the construction of the low-energy effective theory, it involves embedding the SM fermions in representations of the global symmetry $\mathscr{G}$ and then constructing $\mathscr{G}$ invariant operators out of these multiplets and Σ. Such an embedding is sometimes called a spurion; the term spurion refers to the "missing" elements of the multiplet, since after all, the SM particles do not come in full multiplets of the new symmetry $\mathscr{G}$. The incompleteness of these spurious multiplets contributes to the explicit breaking of $\mathscr{G}$ and allows Higgs to acquire a potential via loops of SM fermions.

The appropriate representation in which embedding the SM particles would, in principle, depend on the UV completion of the model. Some attempts towards UV completions of Composite Higgs models have been made (see, e.g., [5, 7, 9]); however, for the purposes of most model building the choice of representation is a "free parameter" of the model. There is, however, good cause to restrict the choice of representation into which the $SU(2)_L$ quark doublet is embedded. As shown in [33], embedding q_L into a bidoublet $(\mathbf{2},\mathbf{2})$ of the custodial $SO(4) \simeq SU(2)_L \times SU(2)_R$ can prevent anomalous contributions to the $Z \to b\bar{b}$ coupling. This restriction forces

Table 1: κ_F in different models.

κ_F	Models
$\kappa_F^A = \sqrt{1-\xi}$	$SO(5)/SO(4)$ – [3, 11]
	$SO(6)/SO(4) \times SO(2)$ – [14–16]
	$SU(5)/SU(4)$ – [17]
	$SO(8)/SO(7)$ – [21, 22]
$\kappa_F^B = \dfrac{1-2\xi}{\sqrt{1-\xi}}$	$SO(5)/SO(4)$ – [11–13, 20]
	$SU(4)/Sp(4)$ – [6]
	$SU(5)/SO(5)$ – [7]
	$SO(6)/SO(4) \times SO(2)$ – [14–16]

one to choose representations that contain a bidoublet in their decomposition under the custodial $SO(4)$ subgroup of $\mathscr{G}$.

To treat the EFT in full generality, one should embed q_L, t_R, and b_R into different multiplets Ψ_q, Ψ_t, and Ψ_b. The kind of representation that the three quarks are embedded into need not be the same. Thus, even for each coset $\mathscr{G}/\mathscr{H}$, there are a bewildering number of possibilities. However, for the vast majority of models the form of κ_F is actually quite restricted. We tabulate a few examples in Table 1.

It might seem strange that so many distinct models lead to so few possibilities for κ_F. In fact, when one examines the structure of the allowed terms in the effective Lagrangian, a general pattern emerges: the lowest order coupling of the Higgs to fermions will generally contain either one or two factors of Σ. For example, in the Minimal Composite Higgs Model (MCHM), the coset group is $SO(5)/SO(4)$, and one can define that a linearly transforming Σ in the **5** of $SO(5)$, which expanded along the H direction, can be expressed as

$$\Sigma(h) = \left(0, 0, 0, \sin\left(\frac{H}{f}\right), \cos\left(\frac{H}{f}\right)\right). \tag{9}$$

With q_L and t_L embedded in the **5**, Yukawa couplings come from the $SO(5)$ invariant effective operator,

$$\left(\overline{\Psi}_q^{\mathbf{5}} \cdot \Sigma\right)\left(\Sigma \cdot \Psi_t^{\mathbf{5}}\right), \tag{10}$$

leading to a term proportional to $\sin(H/f)\cos(H/f)$. Alternatively one could embed q_L into a **10**, t_R into a **5;** in this case the Yukawa term originates from an operator like

$$\Sigma^T \overline{\Psi}_q^{\mathbf{10}} \Psi_t^{\mathbf{5}}, \tag{11}$$

and the interaction is proportional to $\sin(H/f)$ (note that this structure of couplings also depends on the assumption that Higgs forms part of a doublet, whereas other forms of the effective coupling could be possible in a singlet case; see, e.g., the generic forms of the potential in [34]).

In general the structure must be such that the leading term in the trigonometric expansion is H/f. In almost all cases the relevant term will be proportional to either $\sin(H/f)$ or $\sin(H/f)\cos(H/f)$. This argument is certainly not intended to be rigorous; we merely hope to provide some intuition for the fact that the nonlinear nature of a pNGB Higgs boson leads to repeated structures even across different models and choices of representations (see also [35] for a comprehensive review of different Composite Higgs models, and an especially detailed look at the constraints on the $SO(5)/SO(4)$ coset with Run 1 data).

Following the same procedure as in (5), we can expand around the Higgs VEV to find the expression for κ_F, defined by yv/m_F. A coupling of the form $\overline{\psi}\psi \sin(H/f)$ leads to

$$\kappa_F = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi, \tag{12}$$

while a coupling of the form $\overline{\psi}\psi \sin(H/f)\cos(H/f)$ leads to

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}} \approx 1 - \frac{3}{2}\xi. \tag{13}$$

As we stated above, the representation into which we embed t_R and b_R might not be the same; in this case it is quite possible (depending on the details of the model) that the top and bottom couplings to Higgs have different structures. For instance, in the second example above, although t_R is embedded into a **5**, b_R might be embedded into a **10**. As a result the top coupling would scale with $1 - (1/2)\xi$ while the bottom coupling would scale with $1 - (3/2)\xi$.

There are (as always) some interesting exceptions. For example, in [19], with q_L in a **5** and t_R in a **14**, one can derive $\kappa_F \approx 1 - 3\xi$; see also [36]. In some models (for some examples, see [11, 19]) more than one operator can be constructed which contributes to the same Yukawa coupling. The degree to which each operator contributes will, in such cases, be a free parameter and will lead to more complex expressions for κ_F. Such models are interesting insofar as they are exceptions; however, more minimal scenarios will follow the structure we have outlined above.

No mention has been made so far of the leptonic sector. In theory the lepton Yukawas can also be generated via the partial compositeness mechanism (see, e.g., [12]). This means that κ_τ, for instance, would also receive corrections and in minimal scenarios would depend on ξ like κ_F^A or κ_F^B, as defined in Table 1.

3. Tree-Level Effects

In this section we will briefly look at two interesting scenarios that can lead to tree-level corrections to κ_V and κ_F from the integrating-out of heavier states. We will describe these corrections as leading to a new effective ξ_{eff} to be compared with the vanilla prediction for ξ.

The first possibility is that in models with an extra singlet pNGB (such as the $SU(4)/Sp(4)$ and $SU(5)/SO(5)$ cosets), the pNGB potential could induce a VEV for the singlet. This can modify κ_F and κ_V in two ways: firstly a VEV for the singlet η will induce singlet-doublet mixing between η and H. Singlet-doublet mixing (in the elementary case) and its effect on Higgs couplings was studied in detail in [37]. The fact that H mixes with another scalar means that the couplings will be modified by a factor of $\cos\theta$, where θ is the mixing angle between H and η. For small mixing angles,

$$\kappa_V \approx 1 - \frac{1}{2}\theta^2. \tag{14}$$

In this and in the following we are assuming that the singlet is heavier than Higgs and that it makes sense to integrate it out. Generally, in the absence of further tuning, one expects the extra pNGBs to be heavier than Higgs by a factor of $\xi = v^2/f^2$, since this is the amount by which the mass of Higgs has to be tuned to satisfy electroweak precision test [38]. Thus, in models with around 10% tuning, values for the extra pNGB masses of around 300–500 GeV are not unreasonable.

There could also be effects similar to those studied above, arising from higher-dimensional terms in the nonlinear effective theory. As an example we will look at the $SU(4)/Sp(4)$ model. The gauge boson coupling to Higgs and η (the equivalent of (4)) will be (neglecting hypercharge)

$$\frac{H^2}{H^2+\eta^2}\sin^2\left(\frac{\sqrt{H^2+\eta^2}}{f}\right)W^a_\mu W^{a\mu}. \tag{15}$$

As expected, there is no dimension-4 coupling of η to the $SU(2)_L$ gauge bosons, but there are higher order terms involving η which could modify the hWW coupling if η gets a VEV. However, one should also note that the kinetic term in (3) corrects the Higgs kinetic term:

$$\mathscr{L}_{\text{kinetic}} = \frac{\sin^2\left(v_\eta/f\right)}{v_\eta^2/f^2}\left(\partial_\mu H\right)^2 \approx \left(1-\frac{1}{3}\xi_\eta\right)\left(\partial_\mu H\right)^2. \tag{16}$$

After canonically normalising the Higgs field and expanding around small values of $\xi_\eta = v_\eta^2/f^2$ we find that the $\mathcal{O}(\xi_\eta)$ correction to κ_V actually cancels. To leading order in ξ, ξ_η, and θ we have

$$\kappa_V \approx 1-\frac{1}{2}\xi-\frac{1}{2}\theta^2. \tag{17}$$

The correction due to the singlet VEV thus neatly "factorises" into the mass-mixing correction $\mathcal{O}(\theta^2)$ plus the usual compositeness correction $\mathcal{O}(\xi)$. We can thus define a $\xi_{\text{eff}} = \xi+\theta^2$, such that $\kappa_V \approx 1-\xi_{\text{eff}}/2$.

One finds a similar result for κ_F. The singlet VEV modifies κ_F from $\approx 1-(3/2)\xi$ to

$$\kappa_F \approx 1-\frac{3}{2}\xi-\frac{1}{2}\theta^2 \tag{18}$$

and in this case our effective $\xi_{\text{eff}} = \xi + (1/3)\theta^2$.

In the regime where m_η and v are both $\gg v$, the mixing will be small and will scale approximately as

$$\theta^2 \sim \frac{v^2 v_\eta^2}{m_\eta^4} = \frac{1}{g_\eta^4}\xi\xi_\eta, \tag{19}$$

where we have related m_η to f via some coupling: $m_\eta = g_\eta f$.

The amount of tuning present in such a model was analysed in [39]. This coset was also investigated in a cosmological setting in [34, 40], where the singlet η plays the role of the inflation. In such a scenario the size of the singlet VEV has important implications for the scale of inflation, and the mass-mixing of the inflation would be important also for the process of reheating. Moreover, the singlet η and a nonzero value of ξ_η could be a key component of a solution to the matter-antimatter asymmetry in the Universe [41].

If the value of ξ_{eff} were the same for all couplings (i.e., the modifications to κ_V and κ_{F_i} were the same), then the theory would resemble a CH model without any mixing, only with an apparent rescaling of f. However, it is interesting to note that in the above case the inferred values of ξ_{eff} from the measurements of κ_V and κ_F are different, which would in principle allow us to experimentally distinguish between these two scenarios.

Another possibility is that the spontaneous breaking leads to another pNGB doublet of $SU(2)_L$ (a composite two Higgs doublet model). In principle, explicit breaking effects could lead to a mixing between the two doublets. This possibility is discussed in [14, 15] and in a different context in [18], in which the two doublets appear from two different spontaneous breakings at different scales.

In this case we will obtain similar results to our expressions above for ξ_{eff}, with a correction from the mass-mixing at $\mathcal{O}(\theta^2)$ that will be present in the elementary case and the usual correction at $\mathcal{O}(\xi)$ coming from higher dimensional operators (see [42] for a review of the elementary two Higgs doublet model and [37] for an analysis of the Higgs EFT in such a scenario).

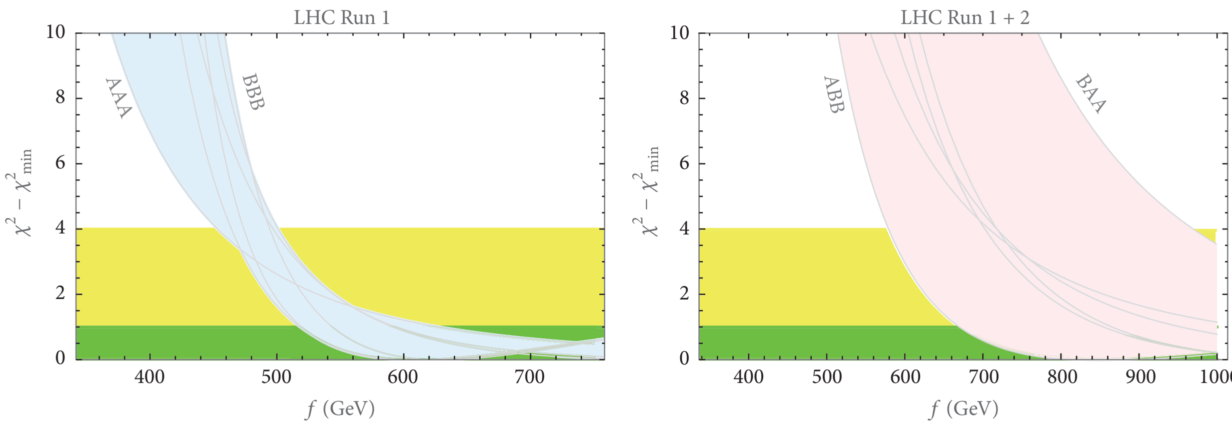
Since we have looked at tree-level corrections to κ_V and κ_F coming from new states in the composite sector, one should also talk about loop level modifications. In principle loops of scalar, fermionic and vector resonances of the strong sector can modify the Higgs couplings. These will arise from higher dimensional ($d \geq 6$) operators in the effective theory, suppressed by factors of f^{4-d}.

4. Status after Run 2

In this section we study the impact of Run 1 LHC data on Composite Higgs models, as well as the improvement which results when adding the 13 TeV results recently released by the collaborations. In Table 2 we summarise the channels considered in the combination of Runs 1 and 2 data from ATLAS and CMS, as well as indicate the coupling modifiers that one would obtain in Composite Higgs models, as discussed previously.

The couplings of the Composite Higgs to gluons and photons, κ_g and κ_γ, are functions of the modifications of the couplings to fermions and gauge bosons, which appear at one-loop order; that is, $\kappa_g^2 = 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t$ and $\kappa_\gamma^2 = 1.59\kappa_V^2 + 0.07\kappa_t^2 - 0.66\kappa_V\kappa_t$ [4, 53]. The modification of the Higgs width, κ_H, is also a function of the coupling modifiers, $\kappa_H^2 \approx 0.57\kappa_b^2 + 0.25\kappa_V^2 + 0.09\kappa_g^2$ (see, e.g., [4]).

We then perform χ^2 fit to the ATLAS and CMS data (when two measurements of the same channel were available, we discarded the worse measurement, or kept both if they were of similar significance. Results from [54, 55] were considered but not included in the fit), with the restriction $\xi > 0$.



(a) (b)

FIGURE 1: $\chi(f)^2 - \chi^2_{\rm min}$ for Run 1 (a) and combination of Runs 1 and 2 (b) datasets. The lines correspond to different choices of fermion couplings $\kappa_F^{A,B}$ for $(\kappa_t, \kappa_b, \kappa_\tau)$. For example, AAA indicates $\kappa_t = \kappa_b = \kappa_\tau = \kappa_F^A$.

TABLE 2: List of 13 TeV channels considered in the fit, with the corresponding κ modifiers. Note that the 7 + 8 TeV Run 1 data was included using the results of the combination of ATLAS and CMS data in [4].

Channel	Refs.	κ-factors
ttH $(H \longrightarrow \gamma\gamma)$	[43–45]	$\frac{\kappa_t^2 \kappa_\gamma^2}{\kappa_H^2}$
ttH $(H \longrightarrow b\bar{b})$	[43]	$\frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2}$
ttH $(H \longrightarrow \tau^+\tau^-)$	[43]	$\frac{\kappa_t^2 \kappa_\tau^2}{\kappa_H^2}$
ttH $(H \longrightarrow WW^*, H \longrightarrow ZZ^*)$	[43]	$\frac{\kappa_t^2 \kappa_V^2}{\kappa_H^2}$
ggF $(H \longrightarrow \gamma\gamma)$	[44, 45]	$\frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H}$
ggF $(H \longrightarrow \tau^+\tau^-)$	[46]	$\frac{\kappa_g^2 \kappa_\tau^2}{\kappa_H^2}$
ggF $(H \longrightarrow WW^*, H \longrightarrow ZZ^*)$	[47–49]	$\frac{\kappa_g^2 \kappa_Z^2}{\kappa_H^2}$
HV $(H \longrightarrow b\bar{b})$	[50, 51]	$\frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2}$
VBF, HV $(H \longrightarrow \gamma\gamma)$	[44, 45]	$\frac{\kappa_V^2 \kappa_\gamma^2}{\kappa_H}$
VBF, HV $(H \longrightarrow WW^*, H \longrightarrow ZZ^*)$	[47, 49, 52]	$\frac{\kappa_V^4}{\kappa_H^2}$

The dependence of the χ^2 function with the scale of new physics f is shown in Figure 1. The green and yellow bands correspond to the one- and two-sigma regions of the fit, and Figures 1(a) and 1(b) correspond to Run 1 and the combination of Run 1 and Run 2, resp. Different choices of fermion representations $\kappa_F^{A,B}$ (as shown in Table 1) lead to different χ^2 dependences.

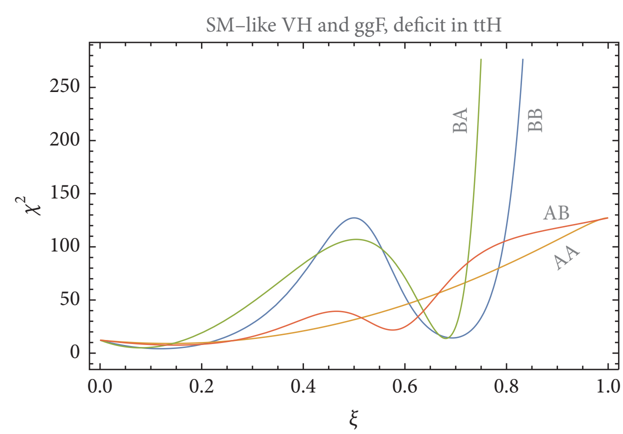


FIGURE 2: $\chi(\xi)^2$ assuming a scenario where a deficit is found in ttH production channels, while other channels remain consistent with the SM. The labels correspond to different hypothesis of $\kappa_F^{A,B}$ for (κ_t, κ_b). In this case, the choice $\kappa_t = \kappa_b = \kappa_F^B$ would be preferred by data. We assume a 20% uncertainty in these channels, except in $gg \rightarrow H \rightarrow \gamma\gamma$ where a 10% accuracy is assumed.

The model-independent limit on f improves from 450 GeV (Run 1) to 600 GeV (Run 1 + 2) at 95% CL, and we see that the most constrained scenario is $\kappa_t = \kappa_F^A$, $\kappa_b = \kappa_\tau = \kappa_F^B$. Moreover, one can see that the spread of limits on the scale f due to these fermion choices increases with the addition of more data. This is a signal that the data is increasingly sensitive to these choices, due to better determination of the Higgs couplings to the heavy fermions. To illustrate this point, assume that at some point in the future a deficit in one channel is observed, whereas other channels remain consistent with the SM. For example, assume that the signal strength of the ttH processes was found to be a third of the SM rate, whereas other processes involving the coupling of Higgs to vector bosons remained consistent with the SM. In this case, certain representations for fermion embeddings of the top and bottom quarks would be preferred by data; see Figure 2.

These limits on f should be compared with the limits of direct searches for new resonances. One would typically expect a set of new resonances, for example, new massive W' and Z', to appear at some scale related to f, $m_{W'} = g_\rho f$, with $g_\rho \lesssim \mathcal{O}(4\pi)$. The value of g_ρ is an input to the effective theory but can be obtained by performing a lattice simulation of the theory and investigating the spectrum of resonances. Its value depends on the specific pattern of breaking as well as the possible electroweak effects. As an indicator of the value of g_ρ in these kinds of models, we draw attention to the work done in the coset $SO(6)/SO(5)$ [56], and in others scenarios [57], where g_ρ was found to be $\mathcal{O}(10)$. In this case, a limit on $f \sim 600$ GeV, would correspond to Z' and W' in the multi-TeV scale, certainly competitive with direct searches for these resonances.

Besides vector resonances, one would expect a tower of fermion resonances, or technibaryons. Typically, these technibaryons are heavier than the vector bound states by a factor of N_{TC}, with N_{TC} the number of colours in the new strongly coupled sector [58, 59]. Hence, naively one would expect fermion resonances again in the multi-TeV scale. Yet, in most Composite Higgs models the mechanism of electroweak symmetry breaking depends on the existence of light technibaryons *(top partners)* with masses of the order of f, contrary to the large-N expectation. This mechanism is being tested by direct searches of heavy partners of the top, with recent Run 2 results already sensitive to the 1.2 TeV region [60], clearly more competitive than the indirect searches in Higgs data if one believed this is the correct mechanism in place. Note, though, that the mass of the top partner is also linked to the amount of fine-tuning in these models. From this point of view the strong limits in top-partners may lead one to consider alternative constructions, such as Composite Twin Higgs models [21, 22, 61, 62], or models involving the see-saw mechanism developed in [18]. In such models the top partners can be significantly heavier without introducing more fine-tuning.

5. Conclusions

In this paper we have summarised the structure of the Higgs couplings (parameterised by κ_V and κ_F) in Composite Higgs models. Although different CH models have very different predictions for the UV theory and the spectrum of higher mass resonances, we have identified generic forms for κ_V and κ_F which hold for many different choices of the coset group and fermion representations.

We have also looked into tree-level effects on these couplings coming from extra states. In particular we studied the interesting possibility that an extra singlet pNGB may acquire a VEV. The modifications to κ_V and κ_F are to leading order just a sum of the corrections in elementary singlet + doublet models and the usual correction expected in composite models. The same can be said for the case in which the Higgs mixes with an extra doublet.

We combined Run 1 and recent Run 2 LHC data to set limits on CH models, finding that different choices for fermion representations lead to a spread of limits but a lower bound on the scale f can be set to 600 GeV. We also discussed how an observed deficit in a Higgs channel such as $t\bar{t}H$ could pinpoint the type of CH model responsible for it.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the Science Technology and Facilities Council (STFC) under Grant no. ST/J000477/1.

References

[1] D. B. Kaplan and H. Georgi, "SU(2) × U(1) breaking by vacuum misalignment," *Physics Letters B*, vol. 136, no. 3, pp. 183–186, 1984.

[2] D. B. Kaplan, H. Georgi, and S. Dimopoulos, "Composite Higgs scalars," *Physics Letters B*, vol. 136, no. 3, pp. 187–190, 1984.

[3] K. Agashe, R. Contino, and A. Pomarol, "The minimal composite Higgs model," *Nuclear Physics B*, vol. 719, no. 1-2, pp. 165–187, 2005.

[4] G. Aad et al., "Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV," *Journal of High Energy Physics*, vol. 08, p. 045, 2016.

[5] G. Ferretti and D. Karateev, "Fermionic UV completions of composite Higgs models," *Journal of High Energy Physics*, vol. 2014, article 77, 2014.

[6] B. Gripaios, A. Pomarol, F. Riva, and J. Serra, "Beyond the minimal composite Higgs model," *Journal of High Energy Physics*, vol. 2009, no. 4, article 070, 2009.

[7] G. Ferretti, "UV completions of partial compositeness: the case for a SU(4) gauge group," *Journal of High Energy Physics*, vol. 2014, no. 6, article 142, 2014.

[8] R. Contino, "The higgs as a composite nambu-goldstone boson," in *Proceedings of the Theoretical Advanced Study Institute in Elementary Particle Physics (TASI '09)*, Physics of the Large and the Small, pp. 235–306, Boulder, CO, USA, June 2009.

[9] J. Barnard, T. Gherghetta, and T. S. Ray, "UV descriptions of composite Higgs models without elementary scalars," *Journal of High Energy Physics*, vol. 2014, no. 2, article 002, 2014.

[10] R. Contino and A. Pomarol, "The holographic composite Higgs," *Comptes Rendus Physique*, vol. 8, no. 9, pp. 1058–1067, 2007.

[11] M. Carena, L. Da Rold, and E. Pontón, "Minimal composite Higgs models at the LHC," *Journal of High Energy Physics*, vol. 2014, no. 6, article no. 159, 2014.

[12] A. Carmona and F. Goertz, "A naturally light Higgs without light top partners," *Journal of High Energy Physics*, vol. 2015, no. 5, article no. 2, 2015.

[13] R. Contino, "A holographic composite higgs model," in *Proceedings of the 18th Conference on High Energy Physics (IFAE '06)*, pp. 215–218, Pavia, Italy, 2006.

[14] S. D. Curtis, S. Moretti, K. Yagyu, and E. Yildirim, "LHC phenomenology of composite 2-Higgs doublet models," *The European Physical Journal C*, vol. 77, no. 8, article 513, 2017.

[15] S. De Curtis, S. Moretti, K. Yagyu, and E. Yildirim, "Perturbative unitarity bounds in composite two-Higgs doublet models,"

Physical Review D: Particles, Fields, Gravitation and Cosmology, vol. 94, no. 5, Article ID 055017, 2016.

[16] J. Mrazek, A. Pomarol, R. Rattazzi, M. Redi, J. Serra, and A. Wulzer, "The other natural two Higgs doublet model," *Nuclear Physics B*, vol. 853, no. 1, pp. 1–48, 2011.

[17] E. Bertuzzo, T. S. Ray, H. De Sandes, and C. A. Savoy, "On composite two Higgs doublet models," *Journal of High Energy Physics*, vol. 2013, no. 5, article 153, 2013.

[18] V. Sanz and J. Setford, "Composite Higgses with seesaw EWSB," *Journal of High Energy Physics*, vol. 2015, article 154, 2015.

[19] A. Azatov and J. Galloway, "Light custodians and Higgs physics in composite models," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 85, no. 5, Article ID 055013, 2012.

[20] C. Csáki, T. Ma, and J. Shu, "Maximally symmetric composite higgs models," *Physical Review Letters*, vol. 119, no. 13, Article ID 131803, 2017.

[21] M. Low, A. Tesi, and L.-T. Wang, "Twin Higgs mechanism and a composite Higgs boson," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 91, no. 9, Article ID 095012, 2015.

[22] R. Barbieri, D. Greco, R. Rattazzi, and A. Wulzer, "The composite twin Higgs scenario," *Journal of High Energy Physics*, vol. 2015, no. 8, article 161, 2015.

[23] R. Alonso, M. B. Gavela, L. Merlo, S. Rigolin, and J. Yepes, "The effective chiral lagrangian for a light dynamical 'higgs particle'," *Physics Letters B*, vol. 722, pp. 330–335, 2013, [Erratum: Phys. Lett.B726,926(2013)].

[24] G. Buchalla, O. Catá, and C. Krause, "Complete electroweak chiral Lagrangian with a light Higgs at NLO," *Nuclear Physics B. Theoretical, Phenomenological, and Experimental High Energy Physics. Quantum Field Theory and Statistical Systems*, vol. 880, pp. 552–573, 2014, [Erratum: Nucl. Phys.B913,475(2016)].

[25] I. Brivio, T. Corbett, O. J. P. Éboli et al., "Disentangling a dynamical Higgs," *Journal of High Energy Physics*, vol. 2014, no. 3, article 024, 2014.

[26] I. Brivio, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, and L. Merlo, "The complete HEFT lagrangian after the LHC run I," *The European Physical Journal C*, vol. 76, no. 7, article 416, 2016.

[27] G. Buchalla, O. Catà, and C. Krause, "A systematic approach to the SILH Lagrangian," *Nuclear Physics B*, vol. 894, pp. 602–620, 2015.

[28] C. G. Krause, *Higgs Effective Field Theories—Systematics and Applications [PhD Thesis]*, Munich, Germany, 2016.

[29] C. G. Callan, S. Coleman, J. Wess, and B. Zumino, "Structure of phenomenological lagrangians. II," *Physical Review A: Atomic, Molecular and Optical Physics*, vol. 177, no. 5, pp. 2247–2250, 1969.

[30] P. Sikivie, L. Susskind, M. Voloshin, and V. Zakharov, "Isospin breaking in technicolor models," *Nuclear Physics B*, vol. 173, no. 2, pp. 189–207, 1980.

[31] D. B. Kaplan, "Flavor at SSC energies: a new mechanism for dynamically generated fermion masses," *Nuclear Physics B*, vol. 365, no. 2, pp. 259–278, 1991.

[32] R. Contino, T. Kramer, M. Son, and R. Sundrum, "Warped/composite phenomenology simplified," *Journal of High Energy Physics*, vol. 2007, no. 5, article 074, 2007.

[33] A. Kaustubh, R. Contino, L. Da Rold, and A. Pomarol, "A Custodial symmetry for Zbb," *Physics Letters B*, vol. 641, pp. 62–66, 2006.

[34] D. Croon, V. Sanz, and J. Setford, "Goldstone inflation," *Journal of High Energy Physics*, vol. 2015, no. 10, article 20, 2015.

[35] B. Bellazzini, C. Csáki, and J. Serra, "Composite higgses," *The European Physical Journal C*, vol. 74, no. 5, p. 2766, 2014.

[36] M. Montull, F. Riva, E. Salvioni, and R. Torre, "Higgs couplings in composite models," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 88, no. 9, Article ID 095006, 2013.

[37] M. Gorbahn, J. M. No, and V. Sanz, "Benchmarks for Higgs effective theory: extended Higgs sectors," *Journal of High Energy Physics*, vol. 2015, no. 10, article no. 36, 2015.

[38] R. Franceschini, G. F. Giudice, J. F. Kamenik et al., "What is the $\gamma\gamma$ resonance at 750 GeV?" *Journal of High Energy Physics*, vol. 2016, no. 3, article 144, 2016.

[39] A. Banerjee, G. Bhattacharyya, and T. S. Ray, "Improving fine-tuning in composite Higgs models," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 96, no. 3, 2017.

[40] D. Croon, V. Sanz, and E. R. M. Tarrant, "Reheating with a composite Higgs boson," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 94, no. 4, Article ID 045010, 2016.

[41] J. R. Espinosa, B. Gripaios, T. Konstandin, and F. Riva, "Electroweak baryogenesis in non-minimal composite Higgs models," *Journal of Cosmology and Astroparticle Physics*, vol. 2012, no. 1, article 012, 2012.

[42] G. Branco, P. Ferreira, L. Lavoura, M. Rebelo, M. Sher, and J. P. Silva, "Theory and phenomenology of two-Higgs-doublet models," *Physics Reports*, vol. 516, no. 1-2, pp. 1–102, 2012.

[43] M. Aaboud et al., "Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector," 2017.

[44] The ATLAS collaboration, "Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb^{-1} pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector," 2017.

[45] CMS Collaboration, "Measurements of properties of the Higgs boson in the diphoton decay channel with the full 2016 data set," 2017.

[46] CMS Collaboration, "Observation of the SM scalar boson decaying to a pair of τ leptons with the CMS experiment at the LHC," 2017.

[47] CMS Collaboration, "Higgs to WW measurements with $15.2\mathrm{fb}^{-1}$ of 13 TeV proton-proton collisions," 2017.

[48] M. Aaboud et al., "Measurement of the Higgs boson coupling properties in the $H \rightarrow ZZ^* \rightarrow 4l$ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector," 2017.

[49] CMS Collaboration, "Measurements of properties of the Higgs boson decaying into four leptons in pp collisions at sqrts = 13 TeV," 2017.

[50] M. Aaboud et al., "Evidence for the H-bb decay with the ATLAS detector," *Journal of High Energy Physics*, vol. 12, p. 024, 2017.

[51] A. M. Sirunyan, "Evidence for the Higgs boson decay to a bottom quark-antiquark pair," 2017.

[52] The ATLAS Collaboration, "Measurements of the Higgs boson production cross section via Vector Boson Fusion and associated WH production in the $WW^* \rightarrow l\nu l\nu$ decay mode with the ATLAS detector at $\sqrt{s} = 13$ TeV," 2016.

[53] M. Gillioz, R. Gröber, C. Grojean, M. Mühlleitner, and E. Salvioni, "Higgs low-energy theorem (and its corrections) in composite models," *Journal of High Energy Physics*, vol. 2012, no. 10, article 004, 2012.

[54] The ATLAS Collaboration, "Search for Higgs boson production via weak boson fusion and decaying to bb in association with a high-energy photon in the ATLAS detector," 2016.

[55] CMS Collaboration, "Search for Higgs boson production in association with top quarks in multilepton final states at $\sqrt{s} =$ 13TeV," 2017.

[56] R. Lewis, C. Pica, and F. Sannino, "Light asymmetric dark matter on the lattice: SU(2) technicolor with two fundamental flavors," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 85, no. 1, Article ID 014504, 2012.

[57] T. Appelquist, R. C. Brower, and G. T. Fleming, "Strongly interacting dynamics and the search for new physics at the LHC," *Physical Review D*, vol. 93, no. 11, Article ID 114514, pp. 65–80, 2016.

[58] G. Hooft, "A planar diagram theory for strong interactions," *Nuclear Physics B*, vol. 72, no. 3, pp. 461–473, 1974.

[59] E. Witten, "Baryons in the *1/n* expansion," *Nuclear Physics B*, vol. 160, no. 1, pp. 57–115, 1979.

[60] "Search for pair production of vector-like top quarks in events with one lepton and an invisibly decaying Z boson. Technical Report ATLAS-CONF-2017-015, CERN, Geneva," 2016.

[61] P. Batra and Z. Chacko, "A composite twin Higgs model," *Physical Review D: Particles, Fields, Gravitation and Cosmology*, vol. 79, no. 9, Article ID 095012, 2009.

[62] C. Csáki, M. Geller, O. Telem, and A. Weiler, "The flavor of the composite twin higgs," *Journal of High Energy Physics*, vol. 2016, no. 9, article 146, 2016.